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Interference Patterns Produced by a Mach-Zehnder Interferometer and a Multiline HF Laser

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The fringe pattern produced by a Mach-Zehnder interferometer illuminated with the light from a hydrogen fluoride (HF) laser operating on a large number of laser lines was investigated. Emphasis was placed on the intensity variations of the infrared fringes that are observed when one element of the interferometer is translated, thereby changing the length of one optical path. An intensity maximum similar to "white-light fringes" is observed when the two arms of the interferometer have equal optical lengths. The experimental results are compared with numerically predicted fringe over

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patterns calculated from the spectral content of the illuminating laser beam. A method is suggested for actively controlling the phases of a number of parallel HF laser amplifiers in high-power phased-array devices.

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A

FIGURES

I. INTRODUCTION

Warren[1] and Turner[2] recently proposed increasing large HF lasers to very high power levels by amplifying the output from a high-power multiline HF oscillator in a series of parallel amplifiers. To obtain a large power density in the far field, Warren[1] suggests processing the output beam from the array of parallel amplifiers with one very large, spherical exit mirror. This mode of operation would require the power amplifiers to be matched in phase, that is, to form a phase-array. Because of the temporal and spatial variations of the amplifying media in the different amplifiers, the phases of the individual beams do not coincide automatically, and a technique must be developed to actively match the optical path lengths of the beams through the different amplifiers. Turner[2] suggests a technique that involves making the amplifiers part of a Mach-Zehnder interferometer with the use of the spatial fringes produced by the interferometer to determine the effective equal optical path lengths. He proposes that the white-light fringes produced by the superposition of the interference fringes of the large number of HF laser lines emitted from the oscillator be observed.

This investigation is concerned with the basic feasibility of this scheme. Questions to be answered include: (1) What fringe patterns are produced by a Mach-Zehnder interferometer when it is illuminated by a multiline HF laser? (2) Is there a clearly discernible "zero-path-difference fringe?" (3) How does the zero path-difference fringe depend on the number and relative strengths of the laser lines? (4) How could this method be used in an active

[1] W. R. Warren, Jr., <u>The Parallel Internal-Master-Oscillator Power-Amplifier for Phase Matching the Output Beams of Multiline Lasers,</u> TR-0078(9990)-6, The Aerospace Corporation, El Segundo, California (16 February 1978).

[2] E. B. Turner, private communication.

control system for a phased-array laser ensemble? All these questions can be answered by studying an empty interferometer with no amplifiers in its arms. The results of such an investigation are presented in the present report.

II. EXPERIMENTAL EQUIPMENT

The details of the optical layout of the experiement are shown in Figure 1. The center of the experiment is a Mach-Zehnder interferometer, which consists of two Au-coated mirrors and two Zn-Se splitter plates. This interferometer is described in Ref. 3. The splitter plates are dielectrically coated for 50% reflectivity at 2.7 μm on one side, and have an antireflection coating on the other side. The interferometer was illuminated simultaneously and colinearly by an intense white-light point source in the visible spectrum (Zr arc source) and a multiline HF laser. The two light sources were added, with the use of a Zn-Se beamsplitter in the input path to the interferometer. At the output of the interferometer, two separate detectors placed very close to each other viewed the visible white-light fringes and the infrared (IR) fringes. The IR detector was a room-temperature In-As detector of about 0.5 mm active diameter; the visible light fringes were observed by a 1P28 photomultiplier fitted with a 0.5-mm pinhole aperture.

The interferometer was illuminated with the multiline output from an HF probe laser.[3,4] For the experiments in this investigation, the laser cavity was equipped with an Au-coated spherical mirror of 200 cm radius and a flat, dielectrically coated coupler with 95% reflectivity at 2.7 μm. The cavity was mounted on Invar rods, and its mode was restricted by a mode aperture; no other mechanical or electro-optical stabilization of its output power or frequency was used. The laser produced 3 W in the TEM_{00} mode on six to seven rotational-vibrational lines of the 2-1 and 1-0 transitions of the HF.

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[3] R. W. F. Gross, R. A. Chodzko, E. B. Turner, and J. G. Coffer, Measurements of the Anomalous Dispersion of HF in Absorption, TR-0079(4764)-2, The Aerospace Corporation, El Segundo, California (15 June 1979)

[4] D. J. Spencer, J. A. Beggs, and H. Mirels, "Small-Scale HF(DF) Chemical Laser," J. Appl. Phys. 48, 1206 (1977).

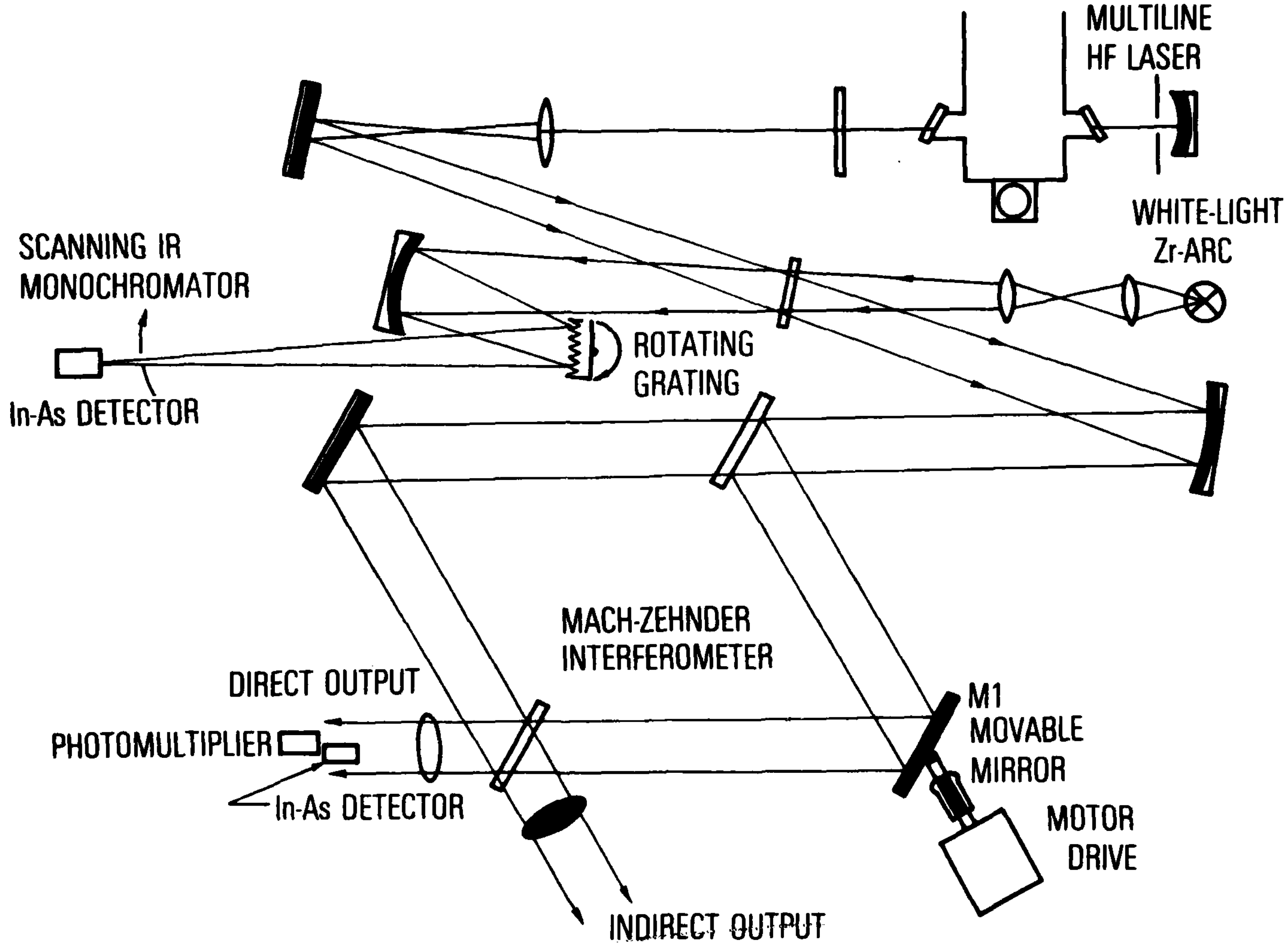


Figure 1. Optical Equipment Layout

The spectral content of the laser output was monitored with a scanning monochromator consisting of a 300-line/mm IR grating mounted on and rotated by a 52-rpm synchronous motor. A room-temperature In-As detector was used as the readout device. Radiation was split-off from the main beam and directed into the scanning monochromator by the same splitter plate that introduced the visible beam into the optical path.

Both the laser beam and the visible light were expanded to a beam of parallel light 2.5 cm in diameter before entering the Mach-Zehnder interferometer. The laser-beam expander was an inverted telescope assembled from a CaF_2 lens with 150 mm focal length and a concave mirror with 1510 mm focal length. The visible light passed a collimator and a lens, and then was recollimated by the concave mirror.

A micrometer driven by a synchronous motor was used to move mirror M1 of the interferometer parallel to the incident light beam, which permitted the length of one interferometer arm to be changed and the fringes to be scanned. The scanning rate could be varied when the driving motor was changed. In this way, it was possible to change the optical path at rates from 5 mm/sec to 16 μm/sec. The high-speed scan was used in all experiments in which the IR fringes produced by the laser were studied. Short scanning times were found to be necessary to avoid instabilities in the fringe records caused by laser frequency, phase, and power fluctuations.[3]

The signals from the two IR detectors were amplified 100 times by dc amplifiers with a bandwidth of about 300 kHz and then displayed on an oscilloscope. The same scope displayed the signal from the photomultiplier viewing the visible fringes.

III. EXPERIMENTAL RESULTS

A. PRODUCTION OF MULTILINE FRINGES

When the Mach-Zehnder interferometer was illuminated by the light from the multiline HF laser, spatial IR fringes were easily observed in its two output beams. The intensity of the fringes and their contrast depended on the number of lasing lines, the difference in optical path between the two arms of the interferometer, and the instantaneous power output of the laser. Fringes were observable even when the interferometer arms were many centimeters from being equal.

In all subsequent experiments, the interferometer was adjusted to produce an "infinite fringe," i.e., it was set such that a single light fringe covered the entire exit aperture of the direct output of the instrument. This condition results when all rejecting surfaces of the interferometer are parallel to each other. The infinite fringe ensures that the small, but finite, apertures of the detectors do not influence the measurements. In this mode of operation, when the direct interferometer output is adjusted to maximum intensity, it carries the full input laser power (less absorption losses), and the indirect interferometer output is covered by a dark fringe.

The output from the interferometer when mirror M1 was driven through about 1.4 cm and the laser operated on six HF lines is shown in Figure 2. The beat pattern observable in the interferometer output is characteristic of all these experiments. A clear zero-path-difference feature cannot easily be discerned in this pattern of beats.

B. DETERMINATION OF THE ZERO PATH-DIFFERENCE FRINGE

To determine the position of the central zero-path-difference fringe, the visible, white-light fringes produced by the Zr arc source, and the multiline IR fringes were recorded simultaneously. White-light fringes were observable only over the short travel distance of M1, about 15 μm around the

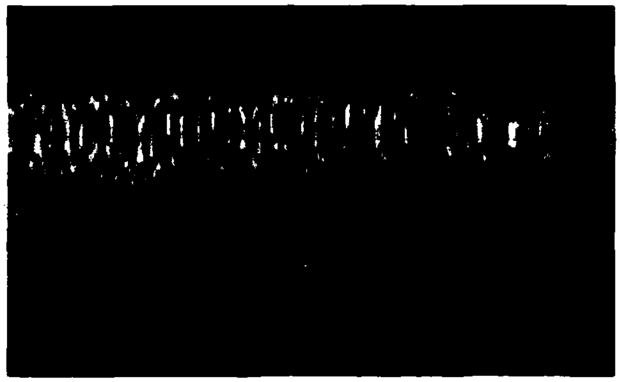
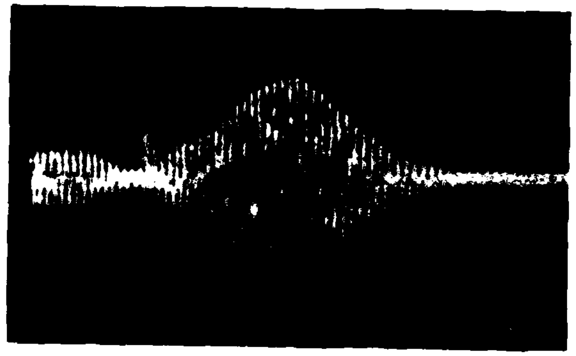


Figure 2. Scan of IR Fringes.
Scan Speed: 1400 μm/div

equal optical path condition of the interferometer; therefore, they permit a fairly accurate determination of this condition in the visible. A scan of the visible and IR fringes near zero path difference between the arms is shown in Figure 3(a). The expanded visible fringes are shown in Figure 3(b). The average wavelength of the visible light is 0.59 μm; therefore, there are about five visible fringes for one IR fringe in Figure 3(a). The white-light fringes have a narrow bell-shaped envelope; the IR fringes form a complicated beat pattern, as shown in Figure 4 in which a larger scan path of mirror M1 has been recorded. In this figure, the visible white-light fringes appear only as a narrow blip to the left of the photograph center.

In Figures 3 and 4, the envelope of the intensity pattern of the IR fringes exhibits a particularly large feature near equal optical path length as defined by the visible fringe pattern. However, the visible and IR central fringes do not coincide, because the two splitter plates differ by about 100 μm in thickness. This discrepancy was found to result in a constant displacement of 11 IR fringes for all recorded experiments. The refractive index of Zn-Se varies strongly between 0.59 and 2.7 μm, and, as a consequence of this dispersion and the difference in the thickness of the plates, the optical paths

(a)



(b)

Figure 3. (a) Scan of IR (Upper Trace) and Visible (Lower Trace) Fringes. Scan Speed: 13.8 μm/div (b) Visible Fringes Expanded. Scan Speed: 4.4 μm/div, $\lambda_m = 0.59$ μm

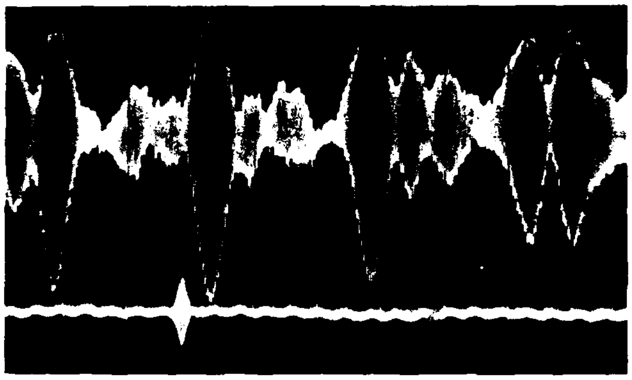


Figure 4. Scan of IR and Visible Fringes.
Scan Speed: 276 μm/div

of the two interferometer arms become equal at two different positions of mirror M1 for the laser and the white-light beams. Nevertheless, a central IR fringe can be identified in the IR beat pattern through study of the visible white light fringes; it is located at the center of the large central beat in Figures 3 and 4.

C. CENTRAL FRINGE DEPENDENCE ON LASER OUTPUT SPECTRAL CONTENT

After the central IR fringe was identified, its dependence on the intensity and number of lines present in the laser output was investigated with the use of the scanning monochromator and a simple numerical computer program that simulated the interference of the laser lines in the interferometer. The scanning monochromator was synchronized to scan the laser output spectrum at the same time as the fringe scan was made. A number of spectral scans were compared, and extensive spectral line switching on a 500-μsec time scale was found. A separate investigation of this problem is in progress. The spectral and fringe scans, therefore, cannot always be fully correlated. Nevertheless, the relative intensities and spectral positions of the lines measured with the monochromator were used

as the input for a simple numerical program that predicts the fringe and beat intensity pattern observed by the interferometer.

It was assumed from the calculations that the various lines in the laser spectrum act as separate, independent oscillators of wavelength λ_i and intensity I_i with arbitrarily narrow linewidths. The interference of one laser line with itself results in an intensity pattern that depends on the optical path difference x between the two interferometer arms. The intensity $I_F^{\pm}$ in the interferometer exits is given by:[5]

$$I_{F_i}^{\pm} = \frac{I_i}{2}\left(1 \pm \cos\frac{2\pi x}{\lambda_i}\right)$$

where the positive sign applies to the direct, and the negative sign to the indirect exit aperture of the interferometer.[5] This expression represents an infinite series of fringes of equal intensity as expected for an arbitrarily narrow, monochromatic light source, with infinite coherence length.

By applying the superposition principle, the interference patterns of n such line oscillators can be added to yield

$$I_F^{\pm} = \sum_{i=1}^{n} \frac{I_i}{2}\left(1 \pm \cos\frac{2\ x}{\lambda_i}\right)$$

The predicted interference pattern has two frequency components. The high-frequency component is the average sum frequency of all lines and results in the observed fringes; the other component, at least for n = 2, is

[5] M. Born and E. Wolf, Principles of Optics, Fourth Edition, Pergamon Press, Oxford, England (1970).

identical with the average difference frequency and, for ≥ 2, describes the beat envelope of the fringes seen in our experiments.

This calculation is the Fourier transform of the line spectrum of the laser output.[5] The interferometer acts as a Fourier transformer, a recognized fact in Fourier spectroscopy.

Using the measured relative line intensities as input to the calculations, we predicted the fringe pattern that was measured. The result of two such correlations is shown in Figure 5. The comparison is generally good, especially if we consider that the intensity fluctuations of the spectra were neglected in the calculations.

To clarify the behavior of the fringe pattern in the vicinity of the central fringe, i.e., near the zero optical path-difference condition, the trigonometric function can be expanded to obtain the intensity in the direct output

$$I_F^+ = \sum_{i=1}^{n} I_i - \sum_{i=1}^{n} \frac{I_i}{2} \left[\frac{1}{2!} \left(\frac{2\pi x}{\lambda_i} \right)^2 - \frac{1}{4!} \left(\frac{2\pi x}{\lambda_i} \right)^4 + \dots \right]$$

and in the indirect output

$$I_F^- = \sum_{i=1}^{n} \frac{I_i}{2} \left[\frac{1}{2!} \left(\frac{2\pi x}{\lambda_i} \right)^2 - \frac{1}{4!} \left(\frac{2\pi x}{\lambda_i} \right)^4 + \dots \right]$$

Note that

$$\sum_{i=1}^{n} I_i = I_{tot}$$

and

$$I_F^- \approx (\pi x)^2 \sum_{i=1}^{n} \frac{I_i}{\lambda_i^2}$$

Since the λ_i differ very little from their average value λ_m, we can replace λ_i by the average value

$$\lambda_m = \frac{1}{m} \sum_{i=1}^{n} \lambda_i$$

$$I_F^- \approx \left(\frac{\pi x}{\lambda_m}\right)^2 I_{tot}$$

which indicates that near the-equal-path length condition, the total power of the laser appears at the direct output. At the indirect output, an error signal is generated that is proportional to x^2 and I_{tot}. Holding I_F^- to a minimum by varying x equalizes the phases of the output beam I_F^+. The phase-control problem has, therefore, been reduced to an intensity control problem with the aid of the interferometer. Moreover, the intensity of the indirect output varies with the square of the phase misalignment $\pi x/\lambda_m$ and should be a sensitive measure of the phase shift.

If we assume that the change in optical path x is the same for all laser lines, i.e., that there is no (anomalous) dispersion present in the intervening medium (amplifiers), and if we also assume that the length of one optical path is controlled in such a way that it always closely equals all others, then for all λ_i

$$\frac{2\pi x}{\lambda_i} \ll 1$$

near the central fringe so that

$$I_F^+ = I_{total} - I_F^-$$

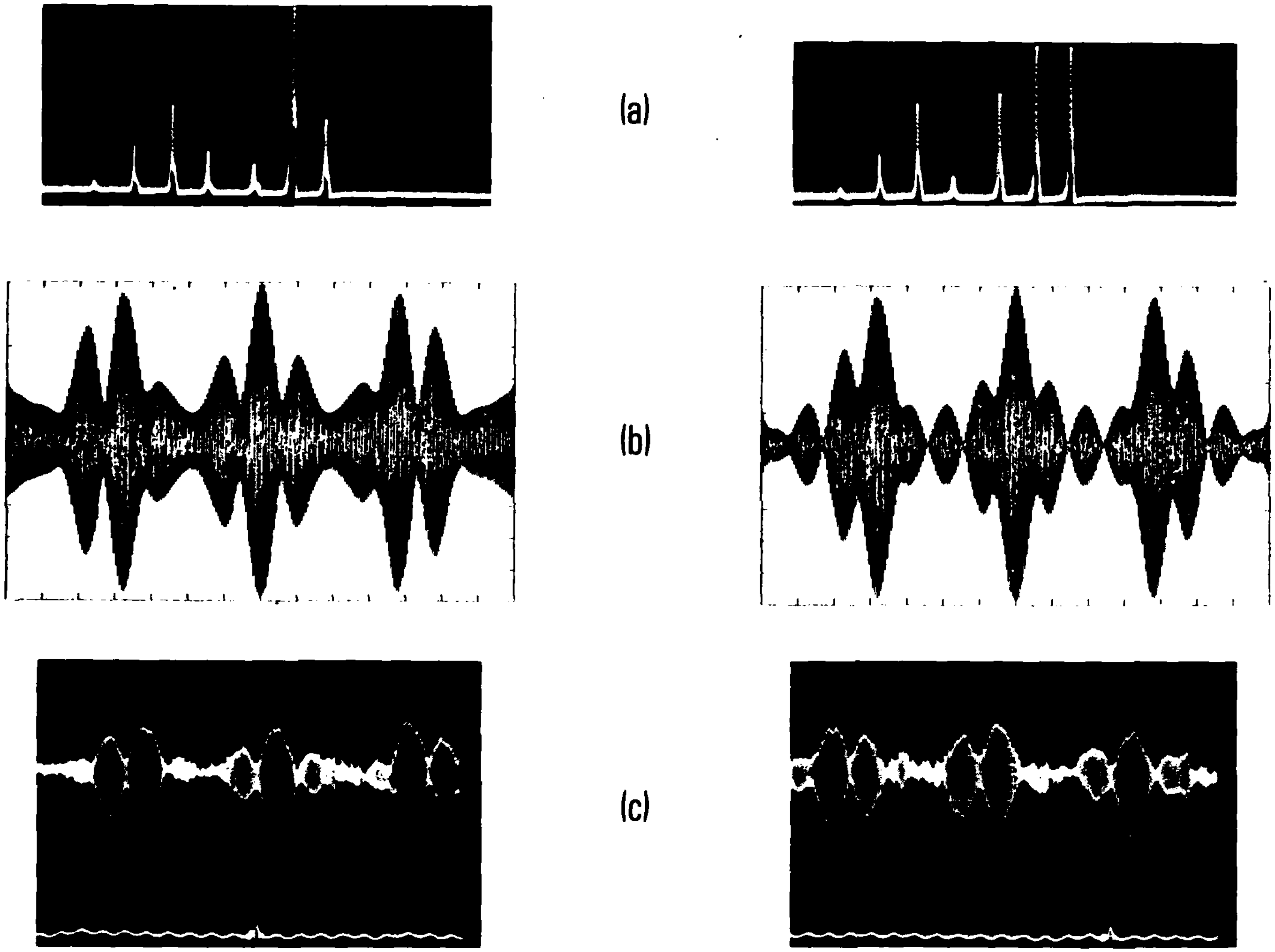


Figure 5. Comparison of Calculated and Measured Fringe Patterns for Two Different Spectral Compositions of the Laser Output. (a) Scan of Laser Spectrum: left, P_1 (5, 6, 7, 8); right, P_2 (6, 7, 8). (b) Fringe Pattern Calculated from (a). (c) Experimental Scan of Fringe Pattern Associated with (a)

IV. CONCLUSIONS

Interference fringes can be easily produced by passing a multiline HF laser beam through a Mach-Zehnder interferometer. The fringes form a complicated beat pattern as a function of time when the optical path length of one arm of the interferometer is changed with respect to the other. The beat pattern can be predicted by a simple numerical calculation that treats the individual laser lines as fully independent monochromatic oscillators of given wavelength and intensity. With the aid of such a numerical calculation and the experimental expediency of white-light visible fringes superimposed on the IR fringes, a single central fringe in the IR fringe pattern can be identified that determines the condition where the optical paths of both arms of the interferometer are equal. This condition can be reached by moving only one of the four optical elements of the Mach-Zehnder interferometer. When the two optical paths are equal, the two beams of the interferometer are in phase. When the interferometer has been adjusted to produce an infinite fringe covering all its exit apertures, the optical paths can be adjusted so that one exit of the interferometer carries the full power of the sum of the two beams (direct exit), and the other carries the error signal produced by any misalignment of the two optical paths (indirect exit). A detector placed into the indirect exit of the interferometer will measure an error signal proportional to the square of the misalignment of the two wavefronts. This signal should permit active and automatic matching of the phases of a number of amplifiers as proposed by Turner,[2] provided the amplifying medium does not exhibit anomalous dispersion. The use of a two-dimensional array of detectors in the indirect exit and of a mirror consisting of a large number of individual segments should also permit the matching of the phases of the two arms over the entire exit aperture, ensuring a high-quality far-field wavefront and diffraction-limited beam quality of the combined beams of a phased-array laser-amplifier system.

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